



Improved thermoelectric power measurements using a four-point technique

J. Corcoran^{a,*}, S. Raja^b, P.B. Nagy^{a,b}

^a Department of Mechanical Engineering, Imperial College London, SW7 2AZ, UK

^b Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, OH 45221-0070, USA

ABSTRACT

The Seebeck coefficient of a material is dependent on its composition and microstructure and is consequently sensitive to service related material degradation; of particular interest is the sensitivity to thermal and irradiation embrittlement which may be exploited for the material characterisation of in service components. Conventionally, thermoelectric measurements are taken using a two-point contact technique which introduces a temperature differential in the test component through a heated 'hot tip' electrode; it is argued that measurements using this methodology are sensitive to the thermal contact resistance between the component and the electrodes. An alternative three- or four-point technique is proposed where heat is introduced to the component remotely which leads to much less sensitivity to contact condition. An experiment is presented that compares the two techniques and demonstrates the improved performance of the four-point technique. Aside from the improved accuracy, the modified technique also facilitates a 'passive' implementation that could be used from continuous monitoring of components in service.

1. Introduction

The Seebeck effect is the development of an electromotive force (EMF) across a material in response to a temperature differential; the ratio of the EMF to the temperature difference is defined as the Seebeck coefficient, S , [1]. For practical, open-circuit, purposes this leads to the expression,

$$S = \frac{\Delta V}{\Delta T}, \quad (1)$$

where ΔV is potential difference and ΔT is the temperature differential across the material.

The Seebeck coefficient of a material, also known as the thermoelectric power (TEP) [2], is dependent on its composition and microstructure [3]. Consequently, a range of studies have established TEP measurements are sensitive to thermal and irradiation embrittlement [4–8], hydrogen and nitrogen embrittlement [9–11], martensite content [12–14], and fatigue damage [15]. The use of the technique for material characterisation therefore appears promising.

Unfortunately the change in the Seebeck coefficient due to subtle material evolution is expected to be modest, while spatial variation may be considerable [16]. An effective means to eliminate uncertainty due to spatial variation is to permanently install the sensor hardware so that measurements are always taken in exactly the same location and repeat measurements are directly comparable. Permanently installing hardware is also attractive so that measurements may be taken in-situ, greatly

increasing the frequency of measurements. The accuracy and stability of the TEP measurements will be crucial; of particular importance will be the sensitivity to surface condition of the component which may not be well controlled in an industrial environment and may evolve with long term operation. The present study is primarily focused at achieving the insensitivity to surface condition required for long term *in situ* measurements.

A more comprehensive description of contact TEP measurements will be presented in the following section but for the present purposed a general arrangement is shown in Fig. 1 a). Contact TEP measurements are made by monitoring the difference in temperature and electrical potential at two separate electrodes pressed in contact with the surface of a material under test, the electrodes incorporate thermocouples which dually serve to monitor the temperature and as the voltage leads across which the potential difference is measured. Conventionally, commercial TEP measurement systems use a 'two-point' technique, where the temperature differential is introduced using a heating element incorporated to one of the electrodes to produce a 'hot tip' while the other passive electrode is left to remain at ambient temperature, as illustrated in Fig. 1 b). A problem may arise if the voltage or temperature of the measurement electrodes do not correspond to that of the component surface. If the interfacial contact introduces either a temperature or electrical potential difference between the surface of the component (T_1, T_2, v_1, v_2) and the measurement electrodes ($T_1^*, T_2^*, v_1^*, v_2^*$) then clearly erroneous calculated values for the Seebeck coefficient will result.

Imperfect interfacial conditions may introduce either electrical or

* Corresponding author.

E-mail address: joseph.corcoran07@imperial.ac.uk (J. Corcoran).

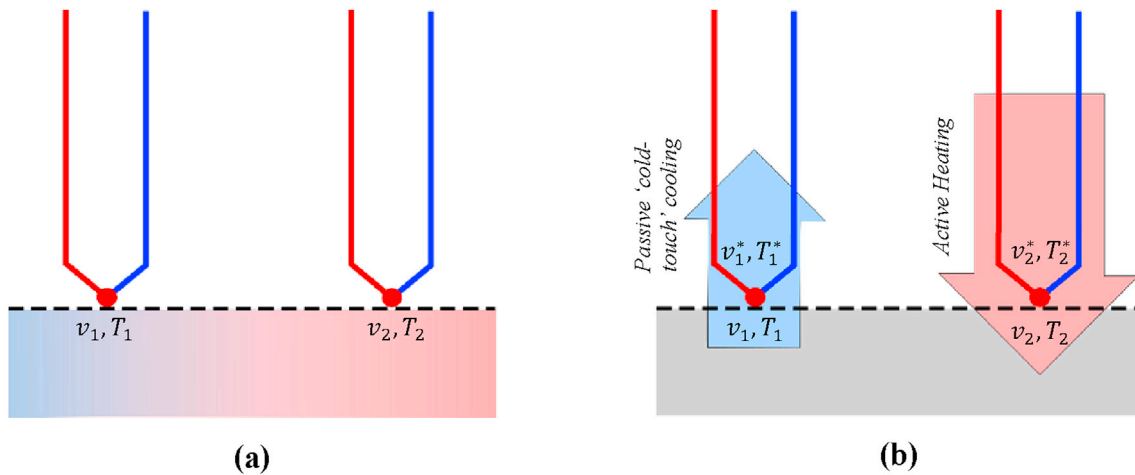


Fig. 1. a) Illustration of a generic contact TEP measurement: two thermocouples are placed in contact with the surface of a component, the thermocouples are used to measure the temperature and also the potential difference between the two points. b) In a conventional two-point measurement, heat is introduced through a heated 'hot-tip electrode'. The terminology is used to indicate that there may be a temperature or electrical potential difference between the sought component surface and the measurement electrodes due to heat flow across the interface.

thermal contact resistance. The electrical contact resistance will be problematic if current flows across the interface which would lead to a potential difference, however, as the electrical potential will be measured using a high impedance differential amplifier (typically 10 MΩ or higher) negligible current will be present and so the electrical contact resistance is not of great significance to the measurement accuracy. Equivalently, the thermal contact resistance will be problematic if there is heat flux across the interface which would lead to a temperature difference. In the case of the 'hot tip' electrode, which introduces heat into the component, the problematic heat flux is intrinsic in the design. A less significant heat flow may exist due to heat conducting into the thermocouples, known as the 'cold-touch' effect. The problem associated with the temperature difference is two-fold; foremost, the inaccuracy in the measured temperature leads to erroneous calculated Seebeck values, and secondly, a spurious additional thermoelectric potential may be present due to the temperature difference across any interfacial material which may have its own Seebeck coefficient. The accuracy of a two-point TEP measurement is therefore limited by the thermal contact resistance.

The importance of thermal contact resistance has long been realized in the design of lab based equipment for measurements on small material samples [2,17–19]. Reducing the thermal contact resistance is the simplest way to reduce the random uncertainty in two-point contact TEP measurements, however, for quantitative thermoelectric NDE of materials undergoing subtle material degradation, the required measurement uncertainty demands more effective techniques. It is possible, though particularly practical, to reduce the thermal gradient between the electrodes and the component by heating or cooling both sides of the thermally active electrode so that heat flow through the contact is minimized [18,20]. Alternatively, another approach is to avoid heating or cooling through the sensing contacts altogether, and introduce the temperature gradient by heating remote locations [2,18,19] the importance of this approach has been highlighted in the literature but has not been demonstrated explicitly, the demonstration in this paper is suggested by Ref. [2]. This is an entirely analogous concept to 4-point electrical resistance measurements where current is injected at remote locations to eliminate contact resistance errors. This study will build on this suggestion and propose an improved three- or four-point technique with reduced sensitivity to interfacial thermal contact resistances; this is of particular concern in *in situ* industrial applications and particularly for monitoring where surface condition may not be well controlled.

The following section will introduce the background to the two-, three- and four-point TEP measurement techniques and examine the differing sensitivity to contact resistances. An experiment will then be

presented that will highlight the limitation of the two-point technique and the necessity of using a three- or four-point approach. Potential industry application will then be discussed and we will propose further opportunities that an improved methodology may afford.

2. Two-, three- and four-point thermoelectric measurement overview

In this section general background to two-three and four-point TEP measurements will be given with particular emphasis on the influence of electrical and thermal contact resistances.

2.1. Contact TEP measurement background

Detailed descriptions of contact TEP metrology can be found in Refs. [2,18,19,21,22]. Contact TEP measurements are conventionally measured using a system similar to the schematic shown in Fig. 2 a). Two thermocouples, taking the form of two separate electrodes, are pressed against the surface of a component. Each thermocouple is made of two separate thermoelements with Seebeck coefficients S_{TC1} and S_{TC2} . A temperature differential in a component, $T_1 - T_2$, produces the thermoelectric potential difference, $v_1 - v_2$, dependent on the sought Seebeck coefficient of the material, S_s ,

$$v_2 - v_1 = \int_{T_1}^{T_2} S_s dT. \quad (2)$$

To calculate, S_s , the four potential differences labelled $\Delta V_1 - \Delta V_4$ in Fig. 2 a) are measured. The potential differences, ΔV_3 and ΔV_4 , are composed of the thermoelectric potential from the Seebeck coefficient and temperature difference of the component, $T_2 - T_1$, and additionally the thermoelectric potential from the Seebeck coefficient and temperature difference of each of the thermoelements, $T_1 - T_0$ and $T_2 - T_0$,

$$\begin{aligned} \Delta V_3 &= \int_{T_0}^{T_1} S_{TC1} dT + \int_{T_1}^{T_2} S_s dT + \int_{T_2}^{T_0} S_{TC2} dT = \int_{T_1}^{T_2} (S_s - S_{TC1}) dT \\ &= (\bar{S}_s - \bar{S}_{TC1})(T_2 - T_1), \end{aligned} \quad (3)$$

where we eliminated the need for integration by assuming that the thermoelectric power remains essentially constant over the temperature range between T_1 and T_2 . It should be mentioned that the linear approximation made in Equation (3) remains valid even when the thermoelectric power in the integrand changes over the temperature range between T_1 and T_2 in a linear way and the averages over the interval are taken as the relevant thermoelectric powers; the Seebeck coefficient at

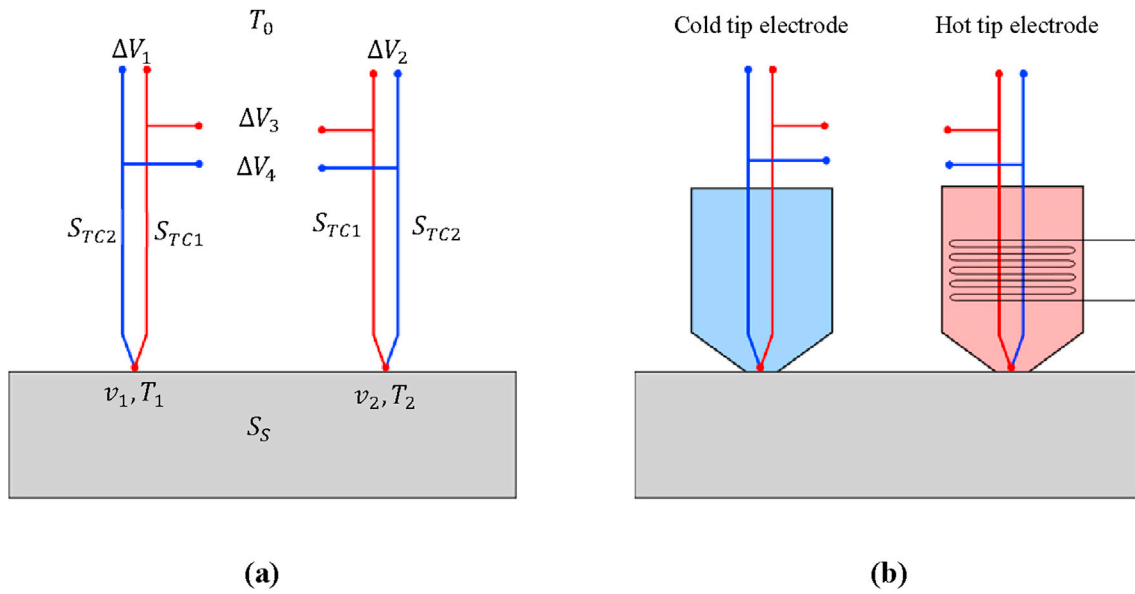


Fig. 2. a) Schematic illustrating a contact TEP measurement, not shown is the heat source to create a temperature gradient. b) Illustration of a conventional 'two-point' measurement where a heating element is integrated into one of the electrodes to introduce the heat.

the reference temperature $(T_1 + T_2)/2$ is denoted throughout by the overbar. Equivalently,

$$\bar{S}_s = \frac{\Delta V_3}{T_2 - T_1} + \bar{S}_{TC1}. \quad (4)$$

It is also possible to take a second potential difference measurement, ΔV_4 , that results in a similar expression to Equation (4),

$$\bar{S}_s = \frac{\Delta V_4}{T_2 - T_1} + \bar{S}_{TC2}. \quad (5)$$

Though this additional measurement is redundant it may be used as an additional measurement to increase accuracy and to check for consistency [22].

In order to infer S_s then S_{TC1} and T_1 and T_2 need to be known. The Seebeck coefficients of common thermoelements, S_{TC1} and S_{TC2} , are usually well documented [23]. Again, since the Seebeck coefficient is temperature dependant, the temperature used for this compensation will be $(T_1 + T_2)/2$. T_1 and T_2 are measured using the standard thermocouple technique. The measured thermocouple voltage, ΔV , is converted to temperature according to the relation,

$$T = \sum_{m=0}^n c_m (\Delta V + V_0)^m \quad (6)$$

where the coefficients, c_m , can be found in the NIST ITS-90 database [24], V_0 is the voltage due to the cold junction which may be calculated from internal temperature measurements of the cold junction, T_0 , and the inverse relation to Equation (6) [22]. $\bar{S}_s$ can then be calculated from Equation (4) or (5).

Conventionally, commercial TEP measurement systems use a 'two-point' technique, where the temperature differential is introduced using a heating element incorporated to one of the electrodes to produce a 'hot tip', as shown in Fig. 2 b).

As mentioned earlier, a temperature difference between the 'hot tip' electrode and the component may arise due to the thermal contact resistance and imposed heat flux. The problem associated with the temperature difference is two-fold; the thermocouple will not reflect the sought temperature of the component surface, and secondly, the temperature differential across any interfacial material will produce a spurious thermoelectric potential. Referring to Fig. 1 b), in the presence of a temperature difference across the 'hot-tip' contact interface,

$\Delta T_i = T_2^* - T_2$, Equation (3) becomes [20],

$$\Delta V_3 = (\bar{S}_s - \bar{S}_{TC1})(T_2 - T_1) + (\bar{S}_i - \bar{S}_{TC1})\Delta T_i \quad (7)$$

where S_i represents the Seebeck coefficient of any interfacial material. The rightmost term represents the systematic error that is introduced due to the combination of imperfect thermal contact resistance and heat flux between the 'hot' tip electrode and component.

This problem is analogous to two-point resistance measurements where current is passed through electrodes into a component and the resulting potential difference is measured using the same electrodes; the potential difference across cables and contacts leads to erroneous measurements. The problem is avoided by using a four-point resistance measurement; two electrodes are used solely for introducing the current and a separate high-impedance pair for measuring potential so that there is negligible current flow in the sensing electrodes. This paper investigates the use of the 'four-point' thermoelectric measurement for *in situ* inspection and monitoring measurements of engineering components.

2.2. Electrical contact resistances

A schematic illustration of an electrical potential measurement is

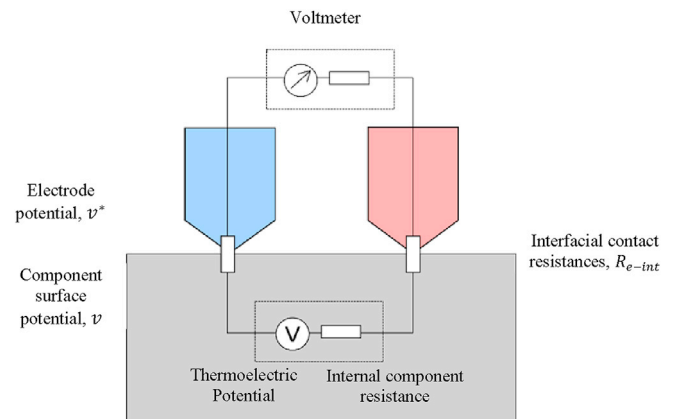


Fig. 3. Schematic representation of the potential drop measurement.

shown in Fig. 3. When electrical current, I , flows across the interfacial electrical contact resistance, R_{e-int} , a potential difference arises between the component surface and the electrode,

$$v - v^* = I R_{e-int}. \quad (8)$$

The thermoelectric potential is measured using a high impedance voltmeter so that negligible current passes across the contact resistances and there will be negligible potential difference between the sought component surface potential and the electrode potential. This brief analysis informs us that the electrical potential measurements are almost entirely insensitive to contact resistances. It should be mentioned that materials of engineering interest have Seebeck coefficients within $\pm 20 \mu\text{V}/^\circ\text{C}$ [3] and therefore the thermoelectric potential is expected to be of the order of microvolts.

2.3. Two-point temperature measurements

For the analysis used in this and the following section it is useful to represent the thermal system as a thermal resistance circuit, further information on thermal resistance networks can be found in Ref. [25]. In this approach temperature (T [$^\circ\text{C}$]) is analogous to electrical potential, heat transfer rate ($\dot{Q}$ [J/s]) is analogous to electrical current, and thermal resistance ($R = \Delta T / \dot{Q}$ [$^\circ\text{C s/J}$]) is analogous to electrical resistance. The system for the two-point measurement system is illustrated in Fig. 4. Similar to the electrical system, in order for there to be a temperature difference between the component surface and the electrode temperature there must be heat transfer across the interfacial thermal contact resistance, R_{th-int} .

$$T - T^* = \dot{Q} R_{th-int} \quad (9)$$

Unlike the electrical potential measurement, where current flow is prevented by the large input impedance of the voltmeter, in the temperature measurement heat flux across the surface contact is forced by the heating of the hot tip electrode to drive the temperature differential in the component. The not insignificant thermal contact resistances combined with the heat transfer results in a temperature difference between the component surface and that measured by the thermocouple, leading to a systematic, contact resistance dependent, error in the TEP measurement.

Minimal heat will be transferred into the cold tip as the vast majority of power will be dissipated through the component in preference. The small heat transfer across the cold tip contact resistance implies there will

be little temperature difference between the component and cold tip temperature sensing point.

2.4. Three- and four-point temperature measurements

The errors that arise from the two-point TEP measurement are caused by the heat transfer from the hot-tip electrode into the component. To avoid this problem we introduce a separate heating element which is not used for measurement, leaving two passive electrodes that are used exclusively for temperature and potential measurements. One or two heating elements may be introduced, creating three- and four-point measurements, respectively.

Fig. 5 illustrates the thermal resistance network for a three-point measurement. The majority of the heat transferred from the hot-tip will be dissipated through the component and only a small fraction will be conducted into the sensing electrodes. As there is very little heat transfer into the sensing electrodes then there will be a much reduced temperature difference between the component and sensing electrodes. The three- and four-point measurement techniques therefore have negligible sensitivity to electrical contact resistances and also significantly reduced sensitivity to thermal contact resistances, leading to more reliable TEP measurements.

3. Experimental demonstration

Measurement equipment was designed and produced specifically to illustrate the differing performance between two- and four-point thermoelectric measurements, a study suggested by Ref. [2] (it should be emphasised from the offset that the design of the equipment is not at all optimised but is designed to provide a fair comparison). An illustration of the measurement equipment is shown in Fig. 6. Four K-type thermocouples are embedded into copper tips and are aligned in a linear formation. The outer two electrodes have heating elements incorporated into them so that they may be used as hot-tips. This arrangement allows two-point and four-point measurements to be taken simultaneously; the two-point technique will use measurements from the outer two electrodes while the four-point technique will use measurements taken from the inner two electrodes but the heat source is alternately provided by one of the outer two. An eight-channel, off-the-shelf, thermocouple reader is used to simultaneously read all four thermocouple outputs as well as the potential differences.

The thermocouples are spring-loaded so that they are forced on to the component with equal force. An $8 \times 40 \times 150$ mm IN100 material

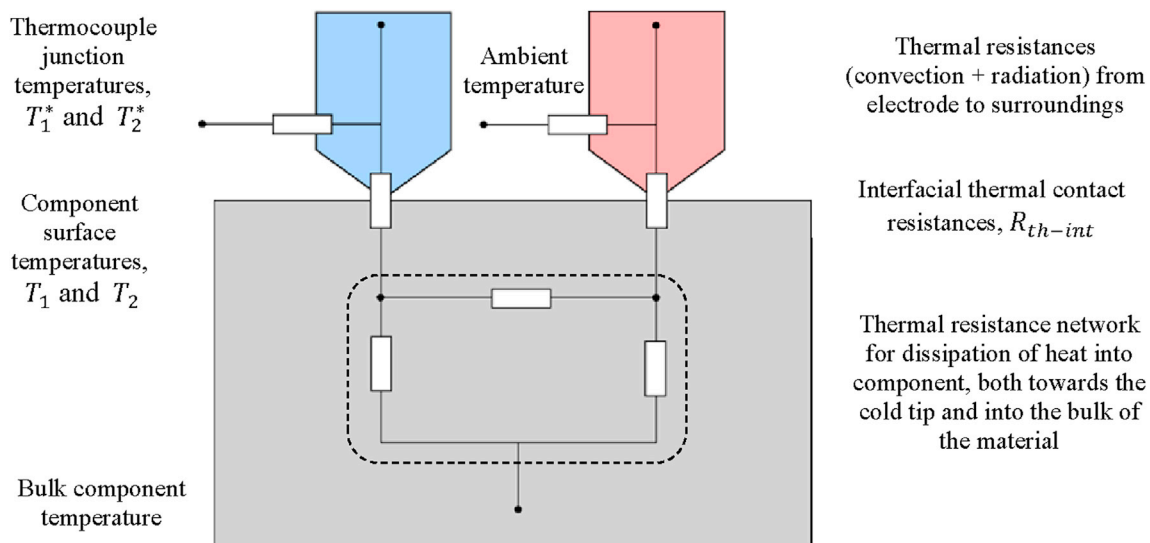


Fig. 4. Schematic showing the thermal resistance model of a two-point TEP measurement.

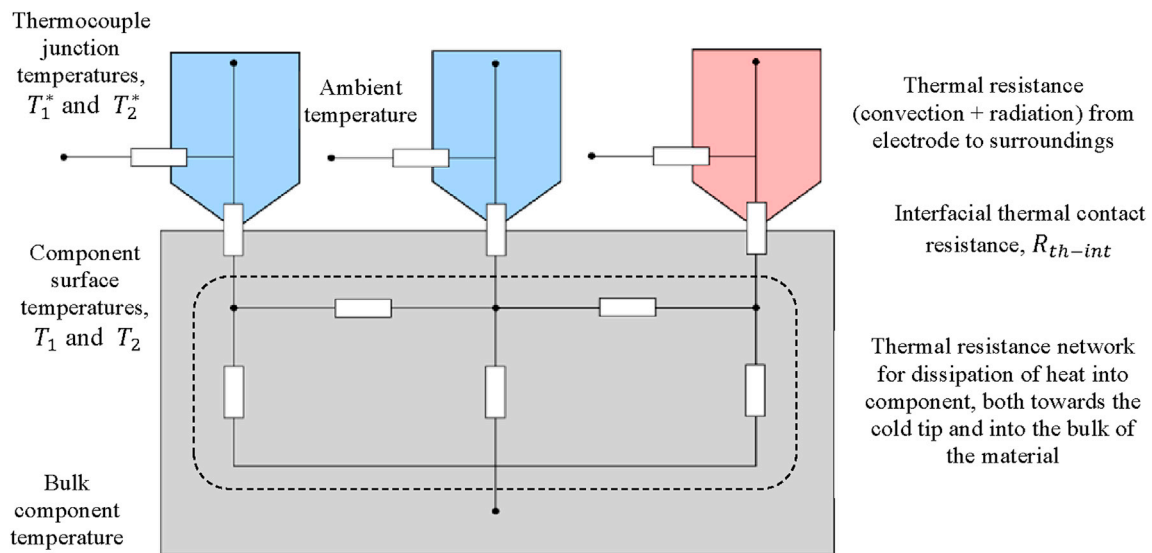


Fig. 5. Schematic showing the thermal resistance model of a three-point TEP measurement.

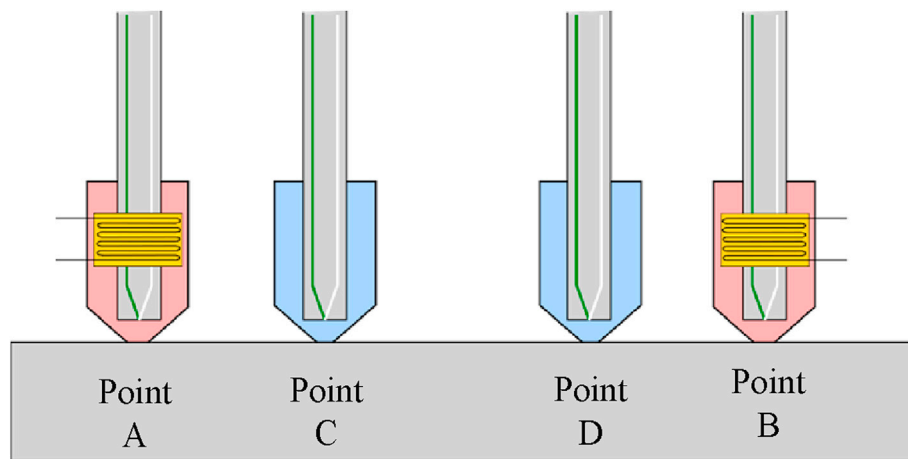


Fig. 6. Illustration of the measurement arrangement. The two outer electrodes, with integrated heating elements, act as a two-point measurement. Simultaneously, the two inner electrodes are used to take four-point measurements, with the heat introduced from the outer two.

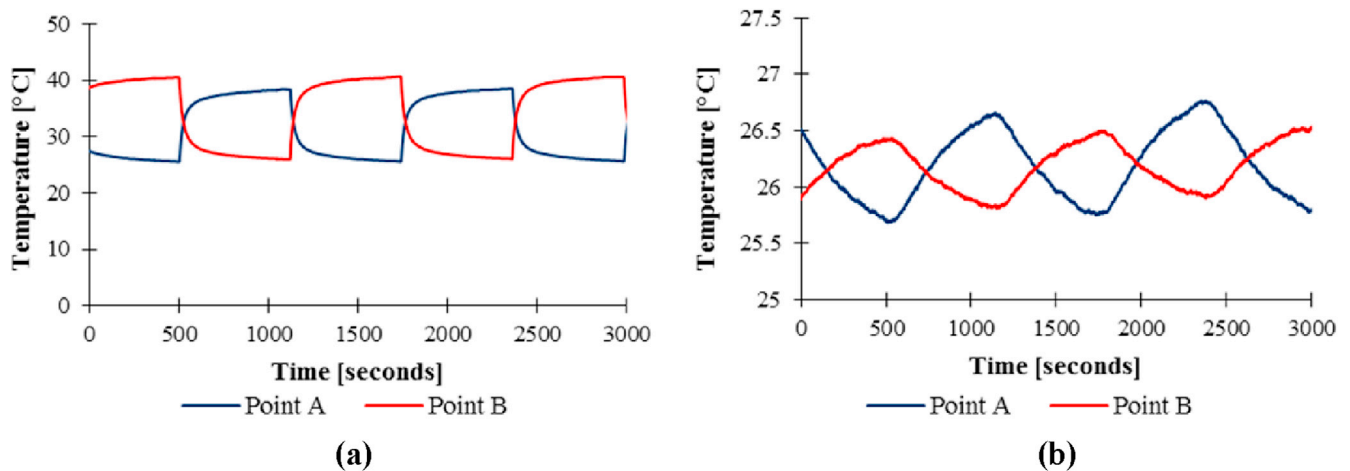


Fig. 7. Example temperature measurements from a) the two point arrangement and b) the four-point arrangement.

sample is used as the test component. Initially the surface of the component is ground and cleaned. Different surface preparations are then imposed in order to vary the thermal contact resistances between all four electrodes and the component. Thermally conductive paste is used to reduce the thermal contact resistance, which is then cleared off and increasing numbers of 0.05 mm stainless steel shims are stacked to increase the thermal contact resistance.

A typical set of temperature measurements is shown in Fig. 7. 1.2 W of electrical power were alternately applied to the two hot-tip electrodes for 600 s periods. This resulted in the approximately 25 °C temperature difference between the outer electrodes, but a temperature difference of typically <1 °C was measured between the inner cold-tips.

For both pairs of electrodes the potential difference is measured using both types of thermoelements, in the K-type thermocouple these are Chromel and Alumel with Seebeck coefficients denoted as S_{K+} and S_{K-} respectively. For the two-point arrangement the two potential differences are denoted by the superscript 2p and the subscript indicating which thermoelement type was used, following from Equation (3),

$$\Delta V_{K+}^{2p} = (\bar{S}_s - \bar{S}_{K+})(T_B - T_A) \quad (10)$$

$$\Delta V_{K-}^{2p} = (\bar{S}_s - \bar{S}_{K-})(T_B - T_A). \quad (11)$$

Similarly, the two potential differences from the four-point arrangement are denoted by the superscript 4p,

$$\Delta V_{K+}^{4p} = (\bar{S}_s - \bar{S}_{K+})(T_D - T_C) \quad (12)$$

$$\Delta V_{K-}^{4p} = (\bar{S}_s - \bar{S}_{K-})(T_D - T_C) \quad (13)$$

A convenient means of calculating S_s from this set of relations is the ‘slope method’, detailed in Refs. [18,19,22]. The potential difference data is plotted against the temperature differences; the gradients will indicate the Seebeck coefficient difference terms of Equations (10)–(13). This method derives values from the use of a large number of data points. It is also possible to calculate the Seebeck coefficient from individual data points, but the gradient approach allows suppression of any influence that causes the $\Delta V = 0$ at $\Delta T = 0$ assumption to be violated. This may include spurious DC offset signals or thermocouple calibration errors. The process is shown in the experimental data of Fig. 8.

Despite the greatly reduced temperature differential, and consequently the much smaller potential difference of the four-point measurement, the gradient of the relationship can clearly be calculated with reasonable accuracy. In practise, a much larger temperature gradient can be imposed.

Each gradient can then be used, in combination with documented values of the Seebeck coefficients $\bar{S}_{K+}$ and $\bar{S}_{K-}$ for that temperature [23], in order to calculate the sought component Seebeck coefficient.

This process is repeated while changing the surface condition for all four electrodes in order to illustrate the influence of changing the thermal contact resistance. The calculated apparent Seebeck coefficient for the two and four-point techniques are shown in Fig. 9; the measurements taken using both K+ and K- thermoelements are shown.

From Fig. 9 it is evident that the two-point measurement technique is far more sensitive to the changing interface conditions than the four-point technique. For the two-point measurement a decrease in the apparent Seebeck coefficient is expected as the electrodes become increasingly thermally isolated from the component; the temperature difference between the electrodes is greater than that which is present in the component, yet the measured potential is unaffected. Additionally, the temperature difference across the stainless steel shims between the heated electrode and the test material will produce a spurious thermoelectric potential that will introduce error into the measurement. With reference to Equation (7), the error in the TEP measurement arises from the term $(\bar{S}_i - \bar{S}_{TCL})\Delta T_i$. This provides an indication to the relative importance of the thermoelectric potential from the interface material as opposed to purely the thermal isolation. The Seebeck coefficient of stainless steel is approximately $-1.2 \mu\text{V}/^\circ\text{C}$ whereas typically the magnitude of thermoelement Seebeck coefficients are typically $>10 \mu\text{V}/^\circ\text{C}$ [3]; this indicates that the influence of thermal isolation is approximately an order of magnitude greater than the influence of thermoelectric potential of the stainless steel interface material in this case. In most cases the interfacial material is not expected to produce a significant potential.

The dependence on thermal contact resistance is particularly concerning regarding *in situ* measurements where the surface preparation of the components may be difficult to control and additionally the required sensitivity is likely to be an order of magnitude smaller than the systematic error demonstrated in Fig. 9.

While discussing thermoelectric measurements, the temperature dependence of the Seebeck coefficient should be given consideration. The Seebeck coefficient of IN100 was measured using the same experimental system (Fig. 8) while changing the average temperature of the component by placing the whole system in an environmental chamber; the results are shown in Fig. 10.

The large temperature dependence of the Seebeck coefficient, here $0.028 \mu\text{V}/^\circ\text{C}^2$, leads to two important considerations. Firstly, the average temperature of the component is an important factor; if the measurement accuracy is required to be $< 0.1 \mu\text{V}/^\circ\text{C}$ then the component average

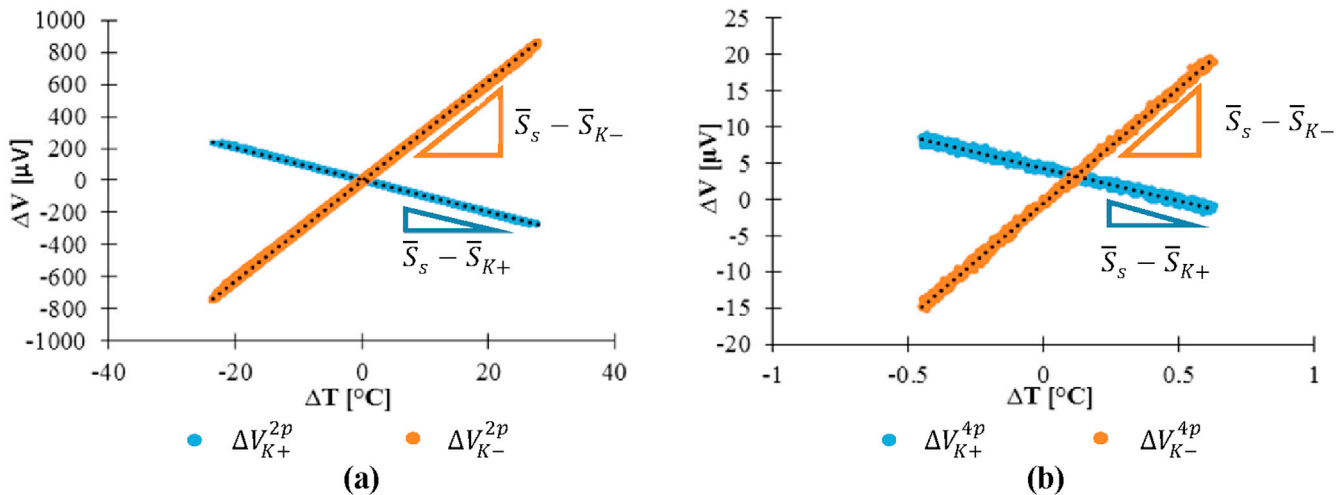


Fig. 8. Example potential difference against temperature difference measurements from a) the two-point arrangement and b) the four-point arrangement. Potential difference measurements taken using the K+ and K- thermoelements are both shown.

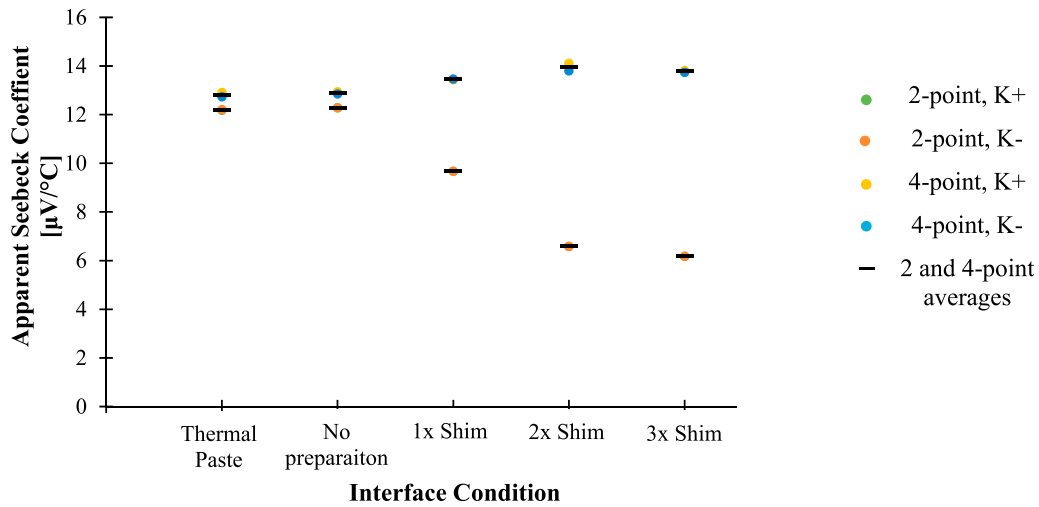


Fig. 9. Apparent Seebeck coefficients for an IN100 sample calculated from the two and four-point arrangements for a range of different surface conditions.

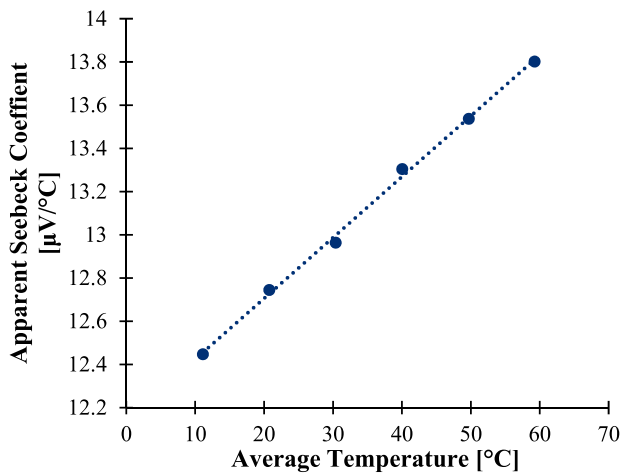


Fig. 10. Temperature dependence of the apparent Seebeck coefficient. Measured using the experimental apparatus illustrated in Fig. 6 and the average temperature manipulated using an environmental chamber.

temperature must be maintained to within approximately 3 °C to allow for like-to-like comparison. Alternatively, the measurements may be corrected using the temperature coefficient of the material; if the temperature coefficient is not already known then it may be obtained as a by-product of the measurement. The other consideration is the assumption in Equation (3), particularly,

$$\int_{T_1}^{T_2} S_S dT = \bar{S}_S (T_2 - T_1) \quad (14)$$

where $\bar{S}_S$ is the average thermoelectric power over the temperature range between T_1 and T_2 . Of course, the average thermoelectric power is equal to the temperature-dependent thermoelectric power at a representative measurement temperature T_m where

$$\bar{S}_S = S_S(T_m). \quad (15)$$

when the thermoelectric power is a linear function of temperature as follows

$$S_S(T) dT \approx S_S \left(\frac{T_1 + T_2}{2} \right) + \left. \frac{\partial S_S(T)}{\partial T} \right|_{T=\frac{T_1+T_2}{2}} \left(T - \frac{T_1 + T_2}{2} \right), \quad (16)$$

the above integration simplifies to

$$\int_{T_1}^{T_2} S_S(T) dT = S_S \left(\frac{T_1 + T_2}{2} \right) (T_2 - T_1) = \bar{S}_S (T_2 - T_1), \quad (17)$$

so that

$$\bar{S}_S = S_S \left(\frac{T_1 + T_2}{2} \right). \quad (18)$$

This assumes that the Seebeck coefficient is essentially constant over the temperature range between T_1 and T_2 , or at least the temperature dependence of the Seebeck coefficient and spatial temperature gradient is linear. This assumption becomes more satisfactory with the three- or four-point measurement as the hot-point that would undermine the assumption becomes remote from the experiment.

4. Discussion

The simple experiment presented in this study illustrates that the four-point thermoelectric measurement is far less sensitive to contact conditions than the two-point technique. It is to be strongly emphasised that the equipment used in this study is far from optimised but was designed to provide a comparison between the two approaches and illustrate the sensitivity to surface conditions. This discussion will be primarily concerned with the design considerations required for implementing the technique to *in situ* measurements of engineering components.

A more sophisticated thermal analogy would have thermal capacitances in parallel with the thermal resistances; these would represent the heat capacity of the different elements of system [25]. If the sensing electrodes have a large thermal capacity then heat will still be transferred across the component-electrode interface which may lead to a detrimental temperature difference between the component surface and thermocouple junction. Additionally, if the test component is at high temperature, and the thermocouple hardware substantial, then heat may be conducted away from the component. The sensing electrodes should therefore be designed to have as small a thermal mass as possible and every effort should be made to have a good thermal contact with the component whilst preventing ‘cold-touch’ heat flow from the component to the electrodes. It is anticipated that the heat-flow into the passive electrodes is substantially less than that imposed by the hot-tip.

It should be noted that there is substantial literature on TEP metrology for small, low thermal conductivity samples [2,19,22,26]

though the conclusions drawn from these reports generally do not translate well to NDE applications where large metallic structures are to be monitored; the literature relating to the latter is sparse. As an example, Martin et al. [26] have concluded that the two-point technique is more reliable than the four-point technique in small, low thermal conductivity samples as it is possible to impose near adiabatic conditions for the heating electrodes and so the ‘cold-touch’ effect becomes dominant. This is contrary to the present example where large engineering components will act as an energy ‘reservoir’ and so significant heat flow from the hot-tip will be required in order to impose the temperature differential, in this case the heat flow out of the thermocouple will be negligible.

In practise, the temperature differential in a three-of four-point measurement does not need to be driven by a hot-tip electrode but may arise from any source of heating (or conversely, cooling). An ideal source of heating should heat the component whilst not using the sensing elements as a conduit for heating; the heat input must not inadvertently ‘short-circuit’ and act through the sensing electrodes and thereby act as a hot-tip electrode.

The temperature differentials that produced the four-point measurements in this study were less than 1 °C. Equivalent accuracy of the calculated apparent Seebeck coefficient may be obtained over a shorter time period using a larger imposed temperature gradient. Equally, however, equivalent accuracy may also be achieved from an even smaller temperature gradient but taking more data points over a longer period. The latter approach be implemented as a ‘passive’ monitoring technique;

the two-sensing electrodes are permanently installed while the very modest temperature gradients required occur incidentally in the component, driven by heat transfer to or from the environment or heat generated from a process or working fluid.

As an example, Fig. 11 a) shows the locations of five temperature sensors installed on a carbon steel pipe of ~200 mm outer diameter and 35 mm wall thickness; two pairs of temperature sensors (in this case resistometric sensors) were present on the outside surface of the pipe, the sensors are separated axially by approximately 0.5 m and two sensors are installed at opposite points on the circumference. Fig. 11 b) shows the measurements taken periodically over 30 days. The pipe surface temperature is elevated to the pipe flow temperature but it is evident that external influences cause systematic temperature differentials between the measurement points. While measurements were not taken on this component (it is archive data) it illustrates the presence of temperature differentials that will exist in industrial components. It is proposed that these ‘passive’ temperature differentials may be exploited to drive the TEP measurement. As no power is required to impose the temperature gradient the energy demand is extremely low and therefore very large numbers of data points may be collected leading to measurements of sufficient accuracy.

5. Conclusions

The Seebeck coefficient of a material is dependent on composition

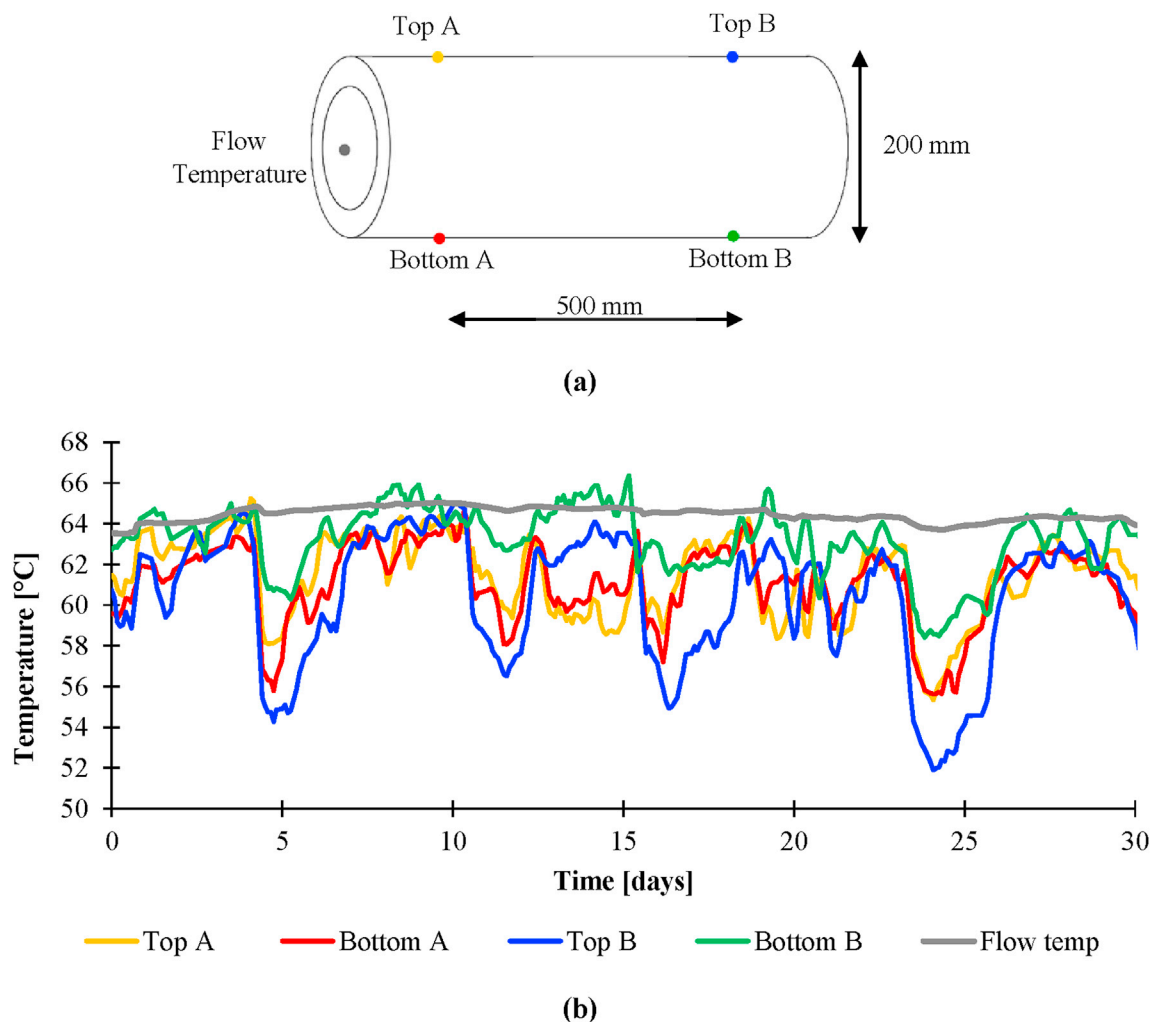


Fig. 11. Thermocouple data showing the incidental temperature variations that exist in industrial components; data provided by Dr. Audun Oppedal Pedersen of ClampOn AS of Bergen, Norway. a) shows the locations of the five thermocouples. b) shows the data collected over 30 days.

and microstructure and is therefore expected to be of interest for the characterisation of materials. Conventionally, thermoelectric measurements are taken using a two-point technique where the heat is introduced through one of the electrodes, creating a temperature difference. Imposing heat transfer through the electrode-component interface leads to sensitivity to the thermal contact resistance and the potential for systematic measurement errors. An improved three- or four-point measurement technique, where heat is introduced remotely from the measurement electrodes, is proposed which is largely insensitive to surface condition. An experiment was conducted demonstrating that the two-point measurements are much more sensitive to contact resistance than the proposed four-point technique.

It is suggested that the improved three- or four-point technique should be used for permanently installed *in situ* measurements of components to achieve the accuracy required for the detection of subtle microstructural degradation. A key motivation for this study is the concept of passive measurements, which this paper lays the technical foundation for. By utilising pre-existing temperature gradients, and eliminating the need to power the heat flow, the information may simply be 'harvested'. The resulting signal from the small temperature gradients may be compensated for by the large number of very low power measurements.

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